AN IMPROVED FORWARDING PROTOCOL FOR UPDATING CHANNEL STATE INFORMATION IN MOBILE FH WIRELESS NETWORKS

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ABSTRACT

The purpose of adaptive forwarding is to provide short-term responses to changes in propagation conditions and network topology in mobile store-and-forward wireless communication networks. The primary need for such short-term responses occurs during the time period between consecutive updates to the routing tables. In this paper a new adaptive-forwarding protocol is described and evaluated for frequency-hop (FH) mobile wireless networks. The forwarding protocol operates in conjunction with adaptive routing and adaptive transmission to provide energy-efficient delivery of packets. Channel state information, which is developed in the receivers of the terminals in the network, is used to estimate the energy requirements of alternative routes for use in the routing protocol. For FH networks the channel state information consists primarily of counts of errors and erasures that are generated in the demodulators and decoders. Since channel state information may become outdated, especially for infrequently used links, it is desirable to provide a mechanism for occasionally testing links that have not handled packets recently. A feature of the new adaptive-transmission protocol is that it employs information packets, rather than control packets, to update the channel state information and thereby benefit the routing protocol without adding overhead traffic to the network load.

I. INTRODUCTION

For many tactical mobile wireless networks it is anticipated that not all pairs of terminals will be within communication range of each other, so the network must be capable of relaying packets through intermediate terminals. Because the network topology, interference environment, and propagation conditions are not constant, the transmission of packets on the links and the routing of packets through the network must be adaptive. Although adaptive-routing protocols are available, their use imposes a certain amount of overhead on the network in order to obtain the information needed to determine the routes and adapt them to changes in the topology, interference, and propagation [1]. In particular, if routing tables are employed, it is necessary to modify these tables as the changes occur. Control packets may be exchanged among the terminals to update the routing tables, but there is a tradeoff between the freshness of the routing tables and the amount of overhead traffic.

We have previously proposed an adaptive-transmission protocol [2] that is very effective in adjusting a link's transmission parameters if the frequency of transmissions on the link is adequate to provide up-to-date channel state information. Similarly, the routing protocols described in [3] can adapt quickly and in an energy-efficient manner if the channel state information is made available by the adaptive-transmission protocol. The combination of these two protocols is particularly effective in identifying and providing alternatives to links and routes that are beginning to fail or are providing poor energy efficiency. However, these protocols alone are not well suited to rapid discovery of links that have suddenly become energy efficient (e.g., because of a reduction in interference or propagation loss).

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In this paper we describe a new adaptive-forwarding protocol that complements the transmission and routing protocols by exploring alternative routes in order to discover links that have improved recently. Prompt identification of improved links increases energy efficiency and enhances the ability of the network protocols to maintain connectivity in a time-varying environment. Interaction among the protocols is necessary to provide coordinated adaptation of the transmission, routing, and forwarding functions of the network.

The use of our adaptive-forwarding protocol to update channel state information is applicable to a wide range of networks and various types of channel state information. For example, the adaptive-forwarding protocol could be used to update the AGC statistics, post-detection signal quality statistics, and symbol error rate statistics for links in a direct-sequence (DS) spread-spectrum system. These statistics and mechanisms for generating them in DS spread-spectrum receivers are described in [4].

In this paper we focus on a FH spread-spectrum network. The primary component of the channel state information for such a network is the very simple side information described in [2] and [5]. This side information consists of counts of errors and erasures that are obtained in the FH spread-spectrum receivers in the manner described in [5]. The side information obtained from the previous transmission on a given link is used by the adaptive-transmission protocol to determine the transmit power level and the code rate for the next packet transmission on the link. The network protocols use the channel state information to determine the energy requirement for the link, which is a component of the channel state information for that link. The energy requirements for the links are employed by the routing protocol to select energy-efficient paths through the network.

The remainder of the paper is organized as follows. We first give a brief overview of transmission and routing in FH networks. We then describe the new adaptive-forwarding protocol and present some results that demonstrate its ability to improve the energy efficiency of mobile spread-spectrum networks. The description of the new forwarding protocol is given in Section III, and the performance evaluations and simulation results are presented in Section IV.

II. TRANSMISSION AND ROUTING

The basic features of FH transmission and reception that are exploited in the transmission, routing, and forwarding protocols are given in [6]. A description of the adaptive-transmission protocol is in [2], the adaptive-routing protocol is described in [3] and [5], and the interaction of these two protocols is explained in [7]. In addition to the packets that contain user information (e.g., voice or data), control packets are employed to update routes and to aid other network functions. An acknowledgment packet is sent in response to each packet that decodes correctly. Throughout this paper, the term *packet* is understood to be an information packet unless it is specifically referred to as a control or acknowledgment packet.

The adaptive-transmission protocol adjusts the power in the transmitted signal and the rate of the Reed-Solomon (RS) code to

respond to variations in the propagation loss and interference on the individual links. The receivers employ errors-and-erasures decoding, and the erasure decisions from the demodulator and the error count from the decoder provide the side information for adaptive transmission. The adaptive-transmission protocol selects the power and code rate for the next packet transmission on this link, and these selections determine the required energy expenditure for that transmission. This energy requirement is reported to the routing protocol for use in selecting an energy-efficient route. Thus the adaptive-transmission protocol provides the necessary channel state information for a link each time a packet is transmitted on that link. If a link is not used for a packet transmission for a long period of time, however, the channel state information may be out of date. One of the goals of the design of a new adaptive-forwarding protocol is to remedy this situation without incurring the additional overhead that would result from more frequent transmission of control packets.

Routing is accomplished using least-resistance routing (LRR) [5], an approach in which channel state information is employed to select the routes of least resistance. The routing metric provides a quantitative measure of the reliability and energy requirement of each link. If the EE-EN metric [3] is employed, the resistance that is assigned to the link from terminal A to terminal B is given by

$$LR(A, B) = \alpha_1 I(A, B) + \alpha_2 U(A, B) + c. \qquad (1)$$

The coefficients α_1 and α_2 are chosen to give the desired emphasis on the individual components of the link resistance. The term c is a constant that provides a minimum value for the resistance. The term $I(A, B)$ characterizes the quality of the link from A to B, and it is based on the counts of errors and erasures. The component $U(A, B)$ provides a measure of the energy required to transmit the packet on the link, and this component depends on the power level and code rate selected by the adaptive-transmission protocol [3]. As a special case, if we set $\alpha_1 = \alpha_2 = 0$, LRR reduces to shortest-path routing, which does not account for link quality or energy consumption.

Although the EE-EN metric can be employed in a wide range of routing protocols, our performance evaluation is for a distance-vector routing algorithm [1]. As in any standard distance-vector algorithm, each terminal periodically makes a broadcast transmission to distribute routing information. In addition, the acknowledgment for a given packet includes the current route resistance to that packet's destination and the channel state information for the next transmission on the link over which that packet was received. The feedback information obtained from the acknowledgment is used by both the adaptive-transmission protocol and the adaptive-routing protocol.

III. ADAPTIVE FORWARDING

As propagation conditions and interference levels fluctuate throughout the network, the amount of energy required to use a given link may change. In some situations such a change may greatly reduce the energy requirement for one or more routes. It is of course desirable that the network learn of reduced-energy routes and account for them in the routing protocol. Our adaptive-forwarding protocol assists other network protocols in accomplishing this objective.

The mechanism by which the network protocols determine the energy requirement for a link is the adaptive-transmission protocol, and this protocol is applied to a given link only if a packet is to be sent over that link. This leads to the possibility that a reduction in the resistance of a particular link might not be observed by the network protocols.

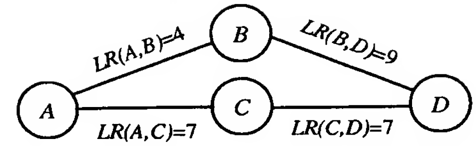

Figure 1. A network with a change in link resistance.

The need for the type of protocol that we propose is illustrated by a simple example shown in Fig. 1. Suppose the route currently used to send packets from terminal A to terminal D employs terminal B and the route resistance is 13. Suppose also there is another route from A to D that goes through terminal C, and that, according to the routing table in terminal A, the route resistance is 14. However, in the time period since A last sent a packet to C, the actual energy requirement for link $A - C$ has decreased to the point that the true resistance of this link is $LR(A, C) = 4$. Because the routing table indicates that route $A - B - D$ has lower resistance than route $A - C - D$, terminal A will continue to send packets to D over route $A - B - D$, even though the use of route $A - C - D$ might save energy. Terminal A will not learn of the decreased energy requirement on link $A - C$ until it transmits to C and receives an acknowledgment.

In order to discover links that have improved recently, our forwarding protocol makes transmissions on alternative links in certain situations. The goal is to obtain current information on outgoing links that offer promising routing opportunities. In the above example, because a reduction in $LR(A, C)$ could result in route $A - C - D$ having lower resistance than $A - B - D$, the forwarding protocol dictates that under certain conditions terminal A will eventually forward to terminal C a packet that is intended for D. We refer to this as *forwarding on an alternative link* or, in simpler terms, *alt-forwarding*. When terminal A forwards a packet on the alternative link $A - C$, the adaptive-transmission protocol discovers that link $A - C$ now requires less energy than indicated in the routing table. The information in the routing table is updated as a result of this discovery.

The primary function of the adaptive-forwarding protocol is to take advantage of local information to modify routes during time periods between normal routing updates. One of the benefits of our adaptive-forwarding protocol is a shorter response time to changes in interference and propagation losses on the links in the network, but this is also provided by some forwarding protocols that do not use alt-forwarding [8]. Another benefit of our adaptive-forwarding protocol is that it utilizes the adaptive-transmission protocol to determine current local information for use in updating routing tables. This latter benefit is derived directly from alt-forwarding.

To be more precise, we say that alt-forwarding occurs for a given packet if that packet was originally scheduled for transmission on one outgoing link but the adaptive-transmission protocol elects to transmit the packet on a different outgoing link. In this situation we also say that the packet was alt-forwarded away from the originally scheduled link. Certain statistics are used to determine if and when alt-forwarding will occur. Each time a link is selected for the transmission of a packet, the forwarding protocol checks the number of transmissions that were made on the link since the protocol last chose to alt-forward a packet away from that link. If this number is large enough, the packet to be transmitted is designated as a candidate for alt-forwarding. Depending on the recent history of transmissions on alternative links and the resistance to the destination for the routes to which these links connect, the forwarding protocol may choose to alt-forward the candidate packet.

A terminal A maintains for each link $A - k$, $N_a(k)$, the number of forwarding attempts on link $A - k$ since the last time a packet scheduled for k was forwarded on an alternative link. If the routing protocol has selected link $A - E$ for a particular packet's forwarding attempt and if $N_a(E) > N_A$, then the alt-forwarding protocol is initiated for this packet. The parameter N_A controls how often forwarding attempts scheduled for a particular link can be considered for forwarding on an alternative link. Below we describe the protocol for selecting an alternative link for the forwarding attempt. If an acceptable link is selected for an alternative forwarding attempt, the packet is forwarded towards its destination along the alternative route. Otherwise the packet is forwarded on link $A - E$ as specified by the routing protocol, and the next packet scheduled for a forwarding attempt to E will trigger the alt-forwarding protocol.

The adaptive-forwarding protocol exercises alt-forwarding at a given terminal on selected links only. In order to explain the method by which the links are chosen for alt-forwarding, we introduce the concept of a *route segment* for a route from one terminal to another. If terminal E has a route to terminal D, and if terminal S has a link to terminal E, then S has a route to D through E. The route from E to D is a route segment for the route that goes from S to D by way of E, and the link from S to E is an *outgoing link* for terminal S. We denote the route resistance for the route segment as $R(E, D)$ and the link resistance for the outgoing link as $LR(S, E)$. Clearly, the route resistance for the route from S to D by way of E is $LR(S, E) + R(E, D)$.

A *candidate link* for alt-forwarding is an outgoing link that connects with a route segment that has low resistance as determined by the routing metric used in LRR. Assume that the alt-forwarding protocol is triggered for a particular packet at terminal S, the packet's destination is D, and the routing protocol has selected link $S - E$ as the default outgoing link. The alt-forwarding protocol finds the alternative link $S - L$ which minimizes $R(L, D)$. The candidate link $S - L$ is not selected in a few situations as discussed in the next paragraph. If the candidate link is not selected, the alt-forwarding protocol examines the link whose corresponding route segment gives the next smallest resistance until an acceptable candidate link is found or there are no remaining candidate links for this destination.

There is not much likelihood of a significant change in the energy requirement on a link over which a packet has recently been forwarded. Therefore, the candidate link to L is not selected if the time that has elapsed since the last forwarding attempt to L is less than τ_U, where τ_U is a fixed parameter. The goal of alt-forwarding is to discover outgoing links for which energy requirements have decreased since they were last used. Obviously, if the routing table indicates the minimum energy level is already sufficient for transmission on the link to L, there is no room for improvement, and the alt-forwarding protocol looks for another link. Finally, the candidate link is not selected if the routing information stored at S indicates that L is likely to forward the packet back to S.

It is important to keep in mind that the alt-forwarding protocol does not rely on additional control packets or other means of obtaining routing information. Alt-forwarding employs information packets that are sent on to their destinations by the routing protocol. Thus, we obtain updates on the outgoing links without adding overhead to the traffic load. The alt-forwarding protocol selects the alternative routes that have the potential to become more efficient if the outgoing link has improved and requires significantly less energy.

IV. PERFORMANCE RESULTS

Computer simulation is used to evaluate the performance of the adaptive transmission, routing, and forwarding protocols when utilized in a FH network. In particular, we consider the performance of the LRR routing protocol employing the EE-EN metric, both with the standard forwarding protocol, which does not use alt-forwarding, and the new adaptive-forwarding protocol. Two network topologies are presented that demonstrate the effectiveness of the adaptive-forwarding protocol. The simulation includes intermittent partial-band interference, which allows us to examine the ability of the forwarding protocol to identify and respond to changes in the interference on the link. All of our numerical results are obtained from a FH radio network simulation which has many features in common with the simulations described in [3].

Each receiver in the simulation has thermal noise with two-sided spectral density $N_0/2$. The energy per binary symbol in the received signal on a given link is denoted by E_s. Each error-control block has 30 fully interleaved codewords. The codes available to the adaptive transmission system are the (32,24) RS code and the (32,12) RS code. The radio transmits a packet as one or two error-control blocks depending on the rate of the code. The transmitter has eight power levels that are defined by $P_i = P_1 + 2(i-1)$ dB for $i = 2, 3, ..., 8$.

Intermittent partial-band interference affects the packet receptions at certain terminals only. The interference is modeled as band-limited white Gaussian noise with spectral density $\rho^{-1} N_I/2$ in a fraction ρ of the frequency band. If $\rho > 0$ we say that partial-band interference is present at a receiver.

A two-state discrete-time Markov chain governs the absence or presence of partial-band interference. In one state there is no partial-band interference, but in the other state partial-band interference is present and has spectral density corresponding to $E_s/N_I = -5$ dB. The time increments for the Markov chain are equal to the transmission time of an error-control block. When in the state corresponding to the absence of partial-band interference, the Markov chain changes states with probability P_J, and it remains in the same state with probability $1 - P_J$. When in the state in which partial-band interference is present, the Markov chain changes states with probability P_N, and it remains in the same state with probability $1 - P_N$. Neither the terminals nor the protocols know any of the parameters or the state of the partial-band interference.

Protocol performance is measured in terms of throughput efficiency and end-to-end success probability. A *valid information bit* is an information bit that is part of a packet that is decoded correctly. An information bit that is correct at the decoder output but is part of a packet that is not decoded correctly (i.e., is not error-free at the decoder output) is not a valid information bit. The *throughput efficiency* is defined as the average number of valid information bits at the decoder output of the destination terminals per unit of energy expended by the transmitters of all terminals in the network. One unit of energy is the amount of energy expended in the transmission of one packet using power P_1 and the (32, 24) RS code. We include routing control packets but not the RTS, CTS, or acknowledgement packets in the measure of throughput efficiency. The energy required to transmit these packets is relatively small compared to information and routing control packets. The *end-to-end success probability* is the ratio of the number of packets that are successfully decoded at their destinations to the number of packets that are generated.

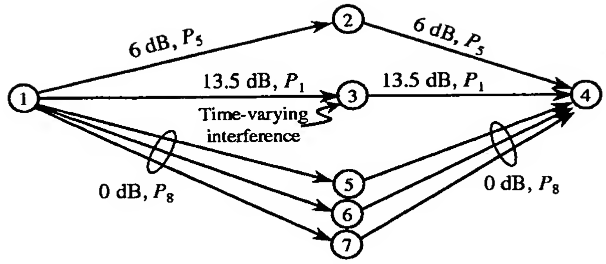

Figure 2. 7-terminal network with the value of E_s/N_0 and the typical power level indicated for each link. For the intermittent interference model $P_J = 0.05$ and $P_N = 0.15$.

The topology used for the first network is illustrated in Fig. 2. All packets in this network are generated at terminal 1 and their common destination is terminal 4. For a transmission at power level P_1, the received energy-to-noise density ratio E_s/N_0 for each of the links is illustrated in the figure. Also shown is the power level that the adaptive-transmission protocol is likely to select for the link. We say that a receiver is *jammed* if it is experiencing partial-band interference. For transmissions to terminal 3, if the receiver is not jammed, the adaptive-transmission protocol typically utilizes the (32,24) RS code. The (32,12) RS code is typically utilized if the receiver is jammed. The parameters used for the EE-EN metric are $\alpha_1 = 0.5$, $\alpha_2 = 2.75$, and $c = 1$.

Even though the presence of jamming does not prohibit terminal 3 from receiving transmissions, utilizing the route through this terminal is not as efficient as the route through terminal 2. On the other hand, when the jamming is not present, the route from 1 to 4 by way of 3 requires the least amount of energy among the possible routes. Regardless of the forwarding protocol, nearly all of the packets are successfully delivered to the destination terminal. The traffic generation rate is held fixed and we examine the ability of the adaptive-forwarding protocol to respond to changes in the interference environment. As illustrated in Fig. 3, there is a considerable improvement in the efficiency of the network protocols if the adaptive-forwarding protocol is utilized to discover the periods when terminal 3 is not jammed.

The topology for the second network is illustrated in Fig. 4. There are 21 terminals and the three terminals labeled j_1, j_2, and j_3 are subjected to intermittent partial-band interference. All packets are generated at terminal S and all have terminal D as their destinations. For this scenario, the level of partial-band interference is very strong. If a terminal is jammed, it is unlikely to receive any transmissions. Illustrated in the figure are the typical power levels that the adaptive-transmission protocol selects for links from terminal S. For the links to j_1, j_2, and j_3, the power levels are for the periods when the receiver is not jammed. The power levels selected for other links are similar.

For the results included in this manuscript, the parameters used for the EE-EN metric are $\alpha_1 = 0.5$, $\alpha_2 = 0.4$, and $c = 1$. Two different models for the behavior of the jamming are examined. In the first model a single Markov chain determines the interference states for all three terminals. In one state all three terminals have partial-band interference with the same value of ρ, and in the other state none of the terminals have partial-band interference. This is referred to as *coordinated* jamming. In the second model, the presence of the jamming is *independent* at each terminal. An independent Markov chain is used to determine the state of the jamming at each of the three terminals.

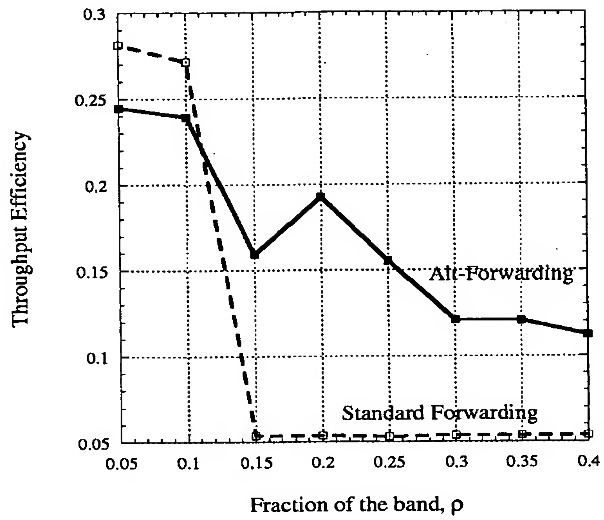

Figure 3. Throughput efficiency for the 7-terminal network for $N_a = 50$ and $\tau_U = 10s$.

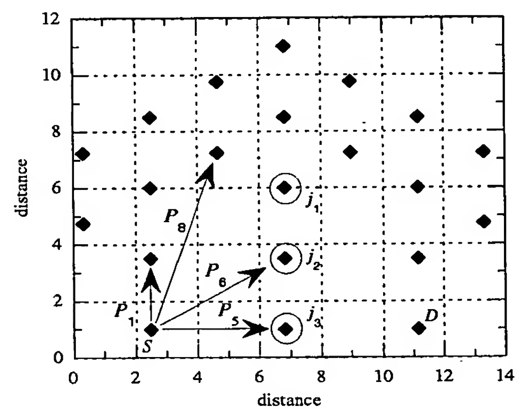

Figure 4. 21-terminal network with 3 terminals subjected to intermittent partial-band interference ($P_J = 0.001$ and $P_N = 0.003$).

In Figs. 5 and 6 the throughput efficiencies obtained for this topology with the two different models for jamming are shown as a function of the packet generation rate at terminal 1. For both jamming models, we consider the standard forwarding protocol, which does not use alt-forwarding, and the new adaptive-forwarding protocol. For the independent jamming model, the end-to-end success probabilities for both forwarding methods are approximately equal and greater than 0.98 at all the generation rates. For the coordinated jamming model the success probability is the same for standard forwarding, since the terminals subjected to jamming are rarely utilized. There is a small decrease in success probability of approximately 0.02 when employing the adaptive-forwarding protocol with the coordinated jamming model, however the throughput efficiency is considerably larger than if the adaptive-forwarding protocol is not utilized.

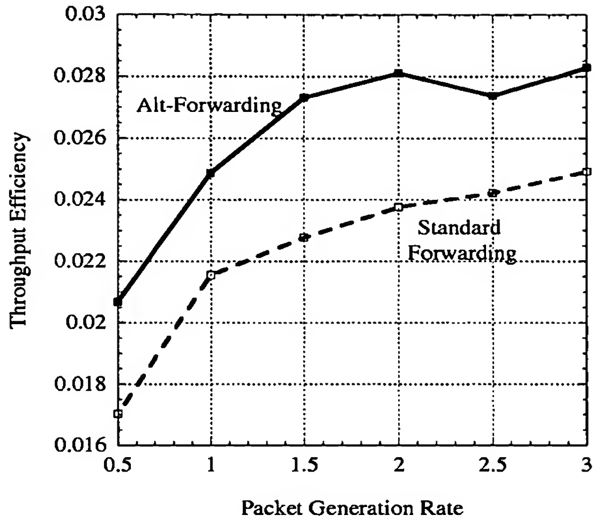

Figure 5. Throughput efficiency for the 21-terminal network with the independent jamming model ($N_A = 100, \tau_U = 10s$).

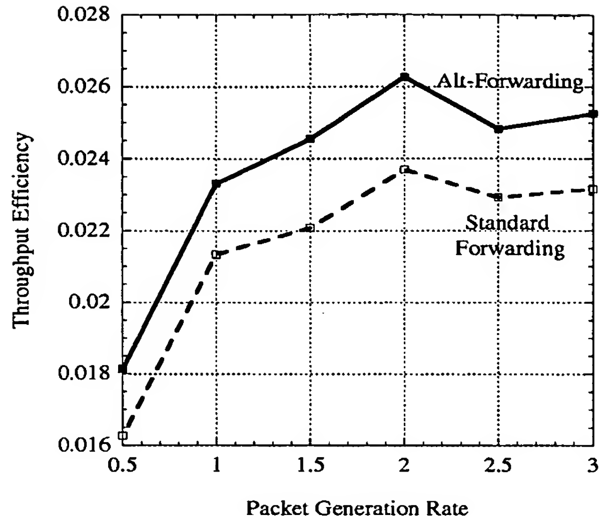

Figure 6. Throughput efficiency for the 21-terminal network with the coordinated jamming model ($N_A = 100, \tau_U = 10s$).

V. CONCLUDING REMARKS

The new adaptive-forwarding protocol interacts with the adaptive-transmission protocol and the adaptive-routing protocol, and it requires no additional channel state information beyond that used by these two protocols. The only side information needed by these three protocols is supplied by the demodulator and decoder in the receiver. The counts of errors and erasures constitute the side information for an FH network, and these two counts are two components of the channel state information. The third component is the energy requirement of the link, which is provided by the adaptive-transmission protocol.

The result of this paper shows that the adaptive-forwarding protocol can decrease the energy expended in a network that contains links whose characteristics vary with time. By judicially forwarding packets on alternative routes, a terminal can update channel state information on infrequently used links. In doing so, it can identify lower energy routes through the network.

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